

# THE FORMATION AND EVOLUTION OF MASSIVE STAR CLUSTERS: HISTORICAL OVERVIEW

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## ABSTRACT

Some factors connecting the evolutionary histories of galaxies with the characteristics of their cluster systems are reviewed. Unanswered questions include: How is one to understand the observation that some globular cluster systems have disk kinematics whereas others do not? Why do some galaxies have cluster systems with unimodal metallicity distributions, whereas others have bimodal metallicity distributions? What caused the average ellipticity of individual clusters to differ from galaxy to galaxy?

## 1. INTRODUCTION

### 1.1. Why there are star clusters and associations?

The existence of multiple stars and star clusters is, as Larson (2003) has recently reminded us, due to the fact that the angular momentum in typical dense cores of giant interstellar molecular clouds (GMCs) is three orders of magnitude greater than can be contained within a single star. The magnetic fields in GMCs cannot dispose of all of this angular momentum. This is so because it has become both dynamically unimportant, and decoupled from the gas, during the later stages of the collapse of these GMC cores. The dense cores of such molecular clouds are therefore expected to fragment into clumps of massive stars. Such concentrations of young stars were named “associations” by Ambartsumian (1954). Associations are now known to come in three flavors: (1) OB-associations, which are comprised of massive young main sequence stars, (2) T-associations, which consist of young intermediate-mass stars that are still contracting to the main sequence, and (3) R-associations (van den Bergh 1966), which are made up of stars that illuminate the dusty interstellar clouds in which they are still embedded.

Since the space density of R-associations is much greater than that of OB-associations such R-associations are particularly suitable for the mapping of nearby Galactic spiral structure (van den Bergh 1968).

## 1.2. Structure of associations.

Within low-density expanding (positive energy) associations one often also finds denser gravitationally stable (negative energy) star clusters (e.g. Blaauw 1964). Some of these clusters, like the small ( $R = 0.3$  pc) clustering near  $\alpha$  Persei (that is located in the emission nebula IC 348) are so small that they clearly have not yet expanded out to their eventual equilibrium radii. Not all associations have the same structure. The 30 Doradus association (see Fig. 1 of Walborn, Maíz-Apellániz & Barbá 2002) in the Large Magellanic Cloud is centered on the single massive compact young OB cluster R136 (which forms the core of the 30 Doradus association), whereas the comparably rich association NGC 604 in M33 (see Fig. 2 of Miskey & Bruhweiler 2003) contains many smaller subclusterings, rather than a single massive core. NGC 206, which is the most luminous association in the Andromeda galaxy (M31), is a slightly older example of a large association that does not have a single massive core. It is presently not known why some associations exhibit such subclustering whereas others do not.

## 2. STAR CLUSTERS AND GALACTIC EVOLUTION

### 2.1. Ages of halo and disk clusters.

Hansen et al. (2002) have found that the faintest white dwarfs in the globular cluster M 4 are 2.5 mag fainter than are the faintest field white dwarfs in the Solar neighborhood. The resulting cooling ages are  $12.7 \pm 0.7$  Gyr for M 4 and  $7.3 \pm 1.5$  Gyr for the Galactic

disk. The relatively young age of the nearby disk has recently been confirmed by Sandage et al. (2003) who determined the age of old field subgiants from their *Hipparcos* parallaxes. These results show, beyond reasonable doubt, that the Galactic disk is  $\sim 5$  Gyr younger than the Galactic halo. As was first emphasized by Berman & Suchkov (1991) the only reasonable way to obtain such a large age difference is by stopping star formation via heating of the Galactic gas to temperatures in excess of that defining virial equilibrium. Such heating would likely have resulted from the strong stellar wind generated by the burst of star formation that accompanied the formation of the Galactic bulge. The fact that the oldest open clusters, such as NGC 6791 and NGC 188, have metallicities that are 1 - 2 times Solar shows that these objects must have been formed from gas that had already been greatly enriched by star and supernova formation.

## 2.2. Cluster formation and galactic star formation rates.

Larsen & Richtler (1999, 2000) have recently shown that the fraction of the total light of galaxies that is locked up in star clusters differs widely from galaxy to galaxy. Star clusters are, for example, almost absent from the very inactive Local Group galaxy IC 1613 (Baade 1963). On the other hand 5.6% of the total V-band light of the nearby starburst galaxy NGC 1569 is emitted by stars in clusters. If massive clusters are mainly formed during intense star bursts then : (1) The history of cluster formation in a galaxy cannot be used as a proxy for the overall history of star formation in that galaxy, and (2) galaxies that exhibit an above average specific cluster frequency (Harris & van den Bergh 1981) probably had at least one major starburst in their history. In view of the apparent correlation between starbursts and the formation of massive clusters it would be particularly interesting to see if the specific cluster frequency is enhanced in IC 10, which is the nearest starburst galaxy. It seems likely (Elmegreen & Efremov 1997, Tan & McKee 2002) that massive

clusters of all ages preferentially formed (and survived) in high pressure environments. This is so because virialized clouds are more tightly bound at high pressures than they are in low pressure environments. Such high pressure might be due to either a high background virial density or to large-scale shocks that are generated during galaxy collisions. It would be interesting to know if the great burst of globular cluster formation, that took place  $\sim 12$  Gyr ago, was also triggered by collisions, or if shocks associated with the reionization of the Universe (See Miralda-Escudé 2003 for a review) might have triggered the great early burst of globular cluster formation.

### 2.3. Cluster formation and galaxy interactions.

Van den Bergh (1960) found that the spiral arms of some late-type interacting galaxies were characterized by particularly patchy (DDO type Sc\*) spiral arms. Since such patches are due to the presence of numerous star clusters and associations, this indicated that strong tidal interactions and mergers can trigger bursts of cluster formation. The notion that interactions between galaxies might enhance the formation rate of massive star clusters (e.g. Schweitzer 1987) has lately received strong support from observations with the *Hubble Space Telescope* [see Whitmore (2003) for a recent review]. The fact that the fraction of all star formation that takes place in massive clusters is apparently enhanced during bursts of star formation indicates that the history of cluster formation in a particular galaxy might be quite different from the overall history of star formation in that same galaxy. In particular it appears likely that the specific cluster formation frequency was enhanced during the early phase of galaxy formation that was dominated by mergers. Proto-planetary disks surrounding young stars might have a high probability of being disrupted in cluster stars than in field stars. It is therefore quite possible that the fraction of stars that form planets may be reduced in early generations of star formation. However, it will be difficult to test

this prediction because the low metallicity of the first generation of stars might also inhibit planet formation. A possible counterexample is provided by the old planet that Sigurdsson et al. (2003) have recently found in the globular cluster M 4. Nevertheless the fact that the disk fraction in very young clusters decreases with age (Lada & Lada 2003) does show that the cluster environment can destroy protoplanetary disks on a time scale of a few million years.

#### **2.4. Formation of star clusters and cluster location.**

Morgan (1958, 1959) devised a new one-dimensional system of galaxy classification, in which the principal classification parameter was central concentration of light in the galaxy image. In the footnotes to his main tables Morgan drew attention to the fact that many spiral galaxies have knots of very active star formation just outside their nuclei. The Arches (age 2 Myr) and Quintuplet (age 4 Myr) are examples of such recently formed super star clusters in our Milky Way system. It is presently not clear why the formation of massive star clusters is favored in a region where differential rotation and tidal stresses would appear to make the formation (and subsequent gravitational collapse) of the massive cores giant molecular clouds particularly challenging. Barth et al. (1995) find that very luminous star clusters may also occur at somewhat greater nuclear distances in the star forming rings that surround some active galactic nuclei.

#### **2.5. Luminosity functions of stars in young star clusters.**

Larson (1999) has recently reviewed the observational evidence on the luminosity function of individual stars in young star clusters. He concludes that “No clear evidence has been found for any systematic dependence of the IMF [initial mass function] on any

property of the system studied, and this has lead to the current widely held view that the IMF is universal, at least in the local universe.” However, the Arches cluster near the Galactic center (Figer et al. 1999) may have a flatter mass spectrum than typical young clusters in the Solar neighborhood. So, perhaps, the mass spectrum of star formation in clusters is not entirely independent of environment after all.

## 2.6. The mass spectrum of cluster formation.

In his book “*Sternhaufen*”, which is the first monograph entirely devoted to star clusters, ten Bruggencate (1927) divides clusters into three classes: (1) globular clusters, (2) open clusters, and (3) star swarms, a class that would, in modern terminology, consist of both moving groups and stellar associations. Ten Bruggencate emphasized the fact that globular clusters have a spheroidal distribution that is centered on the Galactic bulge, whereas open clusters are mainly located in the flattened disk of the Milky Way. Furthermore he pointed to the differences between the color- magnitude diagrams of these two types of clusters, which we now know to be due to systematic differences in age and chemical composition. Perhaps surprisingly, ten Bruggencate did not discuss the systematic difference between the integrated luminosities of typical globular and galactic clusters. Modern work broadly supports the division of Galactic star clusters into (1) old, luminous, metal-poor globular clusters and (2) young, less luminous, and metal-rich open clusters. However, the more extensive data base that is presently available does show intermediate objects such as (a) metal-rich globulars in the Galactic bulge, (b) a few open clusters such as NGC 6791 and NGC 188 with ages of 5-10 Gyr, and (c) some outer halo globular clusters with an ages on only  $\sim 10$  Gyr. Surprisingly the age dichotomy between globulars and open clusters is even more pronounced in the Large Magellanic Cloud (Da Costa 2002) than it is in the Galaxy. On the other hand the systematic difference between the masses

(luminosities) of open and globular clusters is less pronounced in the Large Cloud than it is in the Milky Way, i. e. the LMC open cluster population contains a larger fraction of massive clusters than does that of Galactic open clusters.

### 3. THE EVOLUTION OF CLUSTER SYSTEMS

#### 3.1. Unimodal and bimodal metallicity cluster systems.

It has been known for many years (van den Bergh 1975) that the mean metallicities of globular cluster systems grows with increasing parent galaxy luminosity. This shows that the nature of globular cluster systems is inextricably linked to the characteristics of their host galaxies. This leads one to suspect that the properties of globular cluster systems might also correlate with the Hubble types of their parent galaxies. Unfortunately the number of globular cluster systems for which detailed information on the metallicities of individual clusters has become available is still small. The data are particularly incomplete for spiral galaxies. However, Eerik & Tenjes (2003) have recently published quite extensive information on the metallicity distributions of globular cluster systems surrounding E7-E7 and S0 galaxies. Their data appear to show (97.5% confidence) that elliptical galaxies are more likely to have bimodal cluster metallicity distributions than is the case for S0 galaxies. However, this effect appears to be due to the fact that S0 galaxies are systematically fainter than ellipticals. On average ellipticals therefore have richer globular cluster systems than do lenticulars. The observed effect may be due to the fact that it is difficult to establish bimodality of the cluster metallicity distribution in a poor cluster systems. It would be very interesting to extend the study of the relationship between modality of cluster systems to spiral galaxies. A practical problem is, however, that spirals (1) have a lower specific globular clusters frequency than do ellipticals, and (2) that it is often difficult to distinguish unambiguously between stars and globular clusters in distant spirals.



### **3.2. The flattening of globular clusters.**

The majority of both open and globular clusters in the Galaxy appear as little elongated almost spherical objects. A strikingly different situation is observed to hold in the Large Magellanic Cloud (Frenk & Fall 1982, van den Bergh & Morbey 1984) in which both globular clusters and open clusters are found to be systematically more flattened than are those in the Milky Way System. Such highly flattened objects as NGC 121 in the SMC and NGC 1978 in the LMC are very rare or absent in the Galaxy. The reason for this systematic difference is presently not known. In this connection it is also of interest to note (van den Bergh 1996) that the most luminous globular in a cluster system (e. g. Omega Centauri in the Galaxy, Mayall II in M31, NGC 1835 in the LMC and NGC 121 in the SMC) is often also the most highly flattened.

## **4. DESIDERATA FOR FUTURE WORK**

The topics covered in this review suggest that it might be rewarding to study the following problems in more detail:

- Why is the age distribution of LMC globular clusters so different from that of Galactic globulars? This difference is particularly puzzling because the dichotomy between the masses of open and globular star clusters appears to be much less pronounced in the Large Cloud than it is in the Galaxy.
- We need to understand why the evolutionary histories of different globular cluster systems differ. Why do some have bimodal metallicity distributions, whereas others do not.
- Why are there systematic galaxy-to-galaxy differences between the average flattenings

of individual star clusters? Why do these mean flattenings depend on cluster luminosity, but not on cluster age?

- Some evidence suggests that the mass spectrum with which stars form in clusters is universal, but other data indicate that some clusters may have been formed with “top heavy” mass spectra. Resolving this problem would help us understand both the dynamical and chemical evolution of star clusters.

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